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AI-Enabled Autonomous Area-Keeping for Underwater Vehicles

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Abstract. Autonomous Underwater Vehicles (AUVs), commonly known as submarine drones, provide a critical capability for modern naval operations requiring persistent presence in contested and GPS denied environments. This paper addresses autonomous positioning and area keeping of AUVs within predefined underwater zones using integrated inertial, acoustic, and velocity based navigation systems. Artificial intelligence techniques, including machine learning–based sensor fusion and adaptive decision making, enhance state estimation, navigation robustness, and control performance in uncertain and dynamic environments. By combining AI enabled perception with robust control algorithms, AUVs can maintain precise station keeping and boundary awareness while compensating for ocean currents and environmental disturbances. These capabilities support force protection, intelligence gathering, and undersea surveillance missions, enabling discreet and sustained operations with minimal human intervention..
Keywords: Autonomous Underwater Vehicles (AUVs); Artificial Intelligence; Area Keeping; GPS Denied Navigation; Sensor Fusion; Acoustic Navigation; Station Keeping; Undersea Surveillance; Maritime Security.

1. Introduction

Autonomous underwater vehicles (AUVs) have become essential platforms for underwater exploration, surveillance, and maritime security due to their ability to operate without human presence in harsh and inaccessible environments. Since 2020, advances in sensing, integrated processing, and artificial intelligence (AI) have allowed AUVs to evolve from pre-programmed survey instruments to highly autonomous robotic systems capable of long-duration adaptive missions [1], [2]. These developments are particularly relevant for applications such as seabed mapping, offshore infrastructure inspection, mine countermeasures, and persistent underwater surveillance, where operational resilience and autonomy are critical [3], [4].

A fundamental limitation of underwater operations is the unavailability of Global Navigation Satellite System (GNSS) signals below the water surface. Electromagnetic waves attenuate rapidly in seawater, forcing submerged vehicles to rely on estimation-based navigation methods [5]. Inertial navigation systems (INS) provide autonomous navigation, but suffer from cumulative drift that increases indefinitely over time, even when aided by Doppler Velocity Logs (DVL) [5], [6]. Recent studies confirm that INS/DVL systems alone cannot support the positioning accuracy required for long-duration or safety-critical missions without external corrections [7].

To address this challenge, acoustic positioning systems, such as Long Baseline (LBL), Short Baseline (SBL), and Ultra-Short Baseline (USBL), have been widely adopted. USBL systems offer a favorable balance between implementation complexity, operational flexibility, and accuracy, making them suitable for localized and infrastructure-supported missions [8]. When integrated with probabilistic estimation frameworks such as extended Kalman filters (EKFs) or factorial graph optimization, USBL-assisted navigation demonstrates significant improvements in robustness and accuracy in multipath-affected environments [7], [9]. Beyond navigation, many defense and surveillance missions require autonomous area maintenance, defined as the ability of an AUV to remain within a predefined three-dimensional underwater region for extended periods of time. This capability is essential for harbor protection, underwater infrastructure monitoring, and covert surveillance, where boundary violations can compromise mission effectiveness or security [10]. Environmental perturbations such as ocean currents, hydrodynamic uncertainties, and sensor degradation make accurate area maintenance a non-trivial control problem [11].

Recent research highlights the growing role of AI in underwater navigation, control, and perception. Machine learning techniques have been applied to sensor fusion, acoustic error mitigation, and environmental awareness estimation, outperforming classical model-based approaches under non-Gaussian and time-varying conditions [1], [12]. Deep learning has further enabled advanced perception using sonar and optical sensors, allowing AUVs to classify targets and evaluate underwater scenes in real time, even in low-visibility conditions [13].

In parallel, reinforcement learning-based control strategies have emerged as powerful tools for maintaining position and controlling limited motion. These approaches allow autonomous underwater vehicles (AUVs) to learn adaptive control policies that compensate for unknown hydrodynamic effects and variable ocean currents, achieving improved stability and reduced energy consumption compared to fixed-parameter controllers [14], [15].

The operational relevance of these developments is underlined by the increasing implementation of autonomous underwater systems in modern naval and maritime operations. Recent programs involving large and extra-large AUVs emphasize persistent underwater presence, infrastructure protection, and autonomous decision-making as strategic priorities [16], [17]. In this context, autonomous area maintenance based on artificial intelligence is now recognized as a key capability for future underwater defense and surveillance systems.

2. State of the Art

2.1. Underwater Navigation in GNSS-Denied Environments

Underwater navigation remains a major challenge for all autonomous submersible platforms. Since GNSS signals cannot penetrate seawater, AUVs rely primarily on INS aided by DVL and acoustic positioning systems. Although INS provides continuous navigation estimates, it suffers from unlimited drift, making external position references mandatory for long-duration missions [5], [7].

INS/DVL navigation performance degrades significantly in regions characterized by strong and variable currents or low seabed reflectivity, conditions commonly encountered in coastal and deep-sea environments [6]. Consequently, acoustic positioning systems, especially USBL, have become increasingly relevant for localized monitoring and security tasks due to their flexibility and reduced implementation complexity [8].

A notable advance is the seabed positioning grid concept introduced by Rogobete et al., which uses multiple positioning grid elements (PGEs) enabled by USBL to provide continuous absolute positioning with centimeter-level accuracy within a well-defined underwater area [10]. This infrastructure-assisted approach significantly outperforms free-drift INS/DVL solutions in limited defense scenarios.

2.2. Integrated Acoustic Positioning and Sensor Fusion

Modern underwater navigation systems increasingly rely on tight sensor integration using probabilistic estimation frameworks. Advanced fusion approaches, such as factorial graph optimization and robust Kalman filtering, improve accuracy and robustness by taking into account historical constraints and rejecting acoustic outliers [7], [9].

The grid-based architecture proposed in [10] integrates USBL phase difference processing with Kalman-based estimation synchronized across multiple PGEs. This design allows for continuous absolute position correction and maintains boundary awareness even during temporary degradation of acoustic links.

2.3. Autonomous Area Keeping and Boundary Enforcement

Autonomous area maintenance extends classical station maintenance by enforcing three-dimensional geofenced boundaries. Traditional model-based controllers degrade under uncertain environmental conditions or partial sensor losses [11].

The software-enforced boundary monitoring approach introduced in [10] allows for autonomous trajectory retracement upon approaching or crossing predefined boundaries, even if acoustic positioning is temporarily unavailable. Recent reinforcement learning-based controllers further improve area maintenance by learning disturbance rejection strategies that reduce energy consumption during prolonged operation [14], [15].

2.4. Communications and Infrastructure-Assisted Autonomy

Underwater communication remains constrained by limited acoustic bandwidth and latency. Infrastructure-assisted approaches using fixed nodes on the seabed significantly improve communication reliability for command, control, and data relay in localized missions [18].

The PGE-based communication network proposed in [10] supports full-duplex acoustic communication synchronized with positioning updates. Complementary work by Nita et al. introduces V2X-inspired connectivity principles to enhance positioning resilience and secure interconnection between autonomous marine platforms [19].

2.5. AI-Enabled Perception and Rapid Reaction

Artificial intelligence is increasingly being used for onboard perception, situational assessment and decision-making. Deep learning-based sonar and vision systems enable real-time detection and classification of underwater objects, supporting rapid and autonomous responses to intrusions or anomalies [13].

Infrastructure-assisted positioning and communication significantly reduce response latency, making these systems aligned with emerging naval doctrines that emphasize persistent autonomous underwater surveillance [10], [16].

3. System Characteristics

3.1. Navigation System

The navigation subsystem integrates infrastructure-assisted INS, DVL and USBL positioning to ensure robust localization in non-GNSS environments. High-speed INS estimates are stabilized using DVL velocity measurements, while the absolute positioning is continuously corrected via a USBL grid on the seabed [5], [6], [8], [10].

Sensor fusion is implemented using EKF or factor graph approaches, which provide robustness against multipath propagation and non-Gaussian acoustic noise [7], [9].

3.2. Autonomous control based on artificial intelligence

AI improves both estimation and control. Machine learning models dynamically assess sensor reliability and adjust fusion weights in real time, improving robustness under degraded conditions [1], [12].

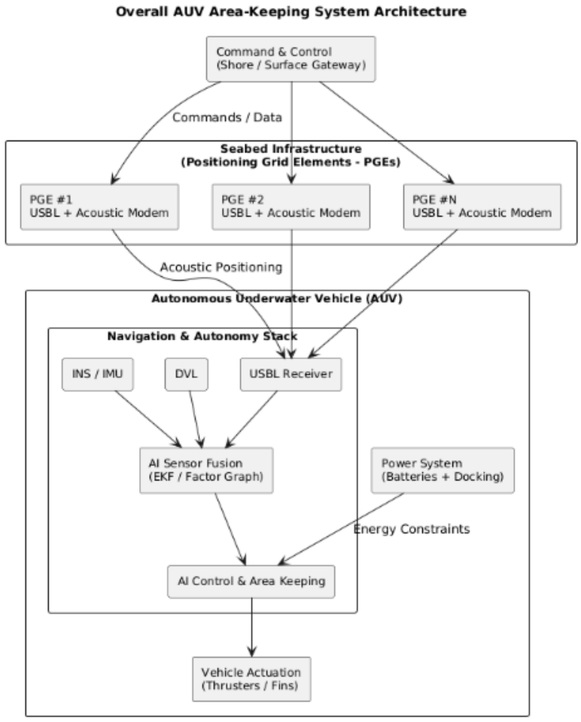

Figure 1. Overall System Architecture Block Diagram

Reinforcement learning-based controllers adapt to unknown hydrodynamic perturbations, providing improved stability and energy efficiency during extended surface-maintaining missions [14], [15].

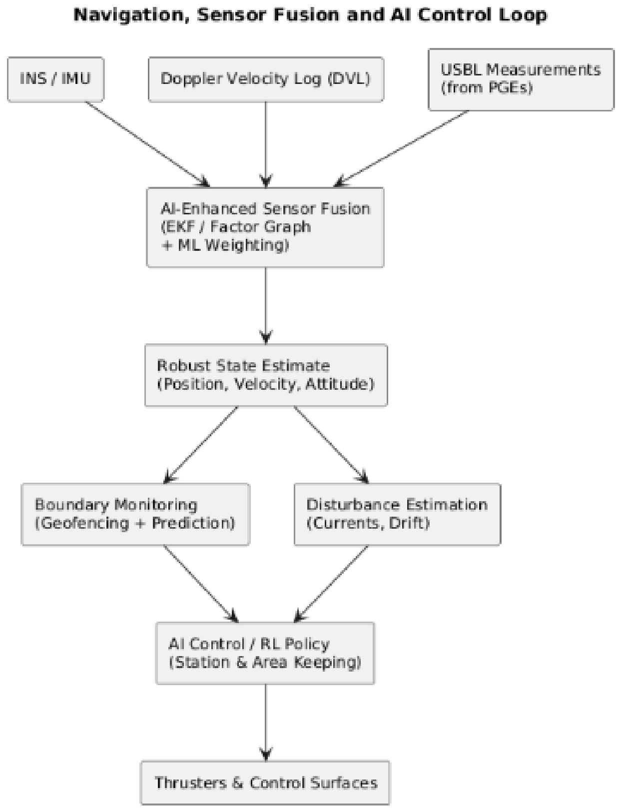

Figure 2. Navigation, Sensor Fusion, and AI Control Block Diagram

3.3. Communications and Energy Management

Full-duplex acoustic modems integrated into the PGE provide infrastructure-assisted communication for positioning data, commands, and alerts [10], [18]. Autonomous docking and underwater recharging enable persistent operation, supported by energy-aware mission planning algorithms that optimize endurance [20].

3.4. Positioning and Limited Area of Study Monitoring

Continuous monitoring of fused navigation data against virtual boundaries requires strict geofencing. AI-assisted prediction anticipates boundary violations, allowing proactive correction. Conservative containment behavior is maintained even during temporary sensor degradation [10], [11].

3.5. Rapid Response and AI

AI-based perception enables detection and classification of intruders, mines, and anomalies. Upon detection, autonomous behavior adaptation and immediate reporting via acoustic grid significantly reduce response time compared to operator-driven systems [10], [13], [16].

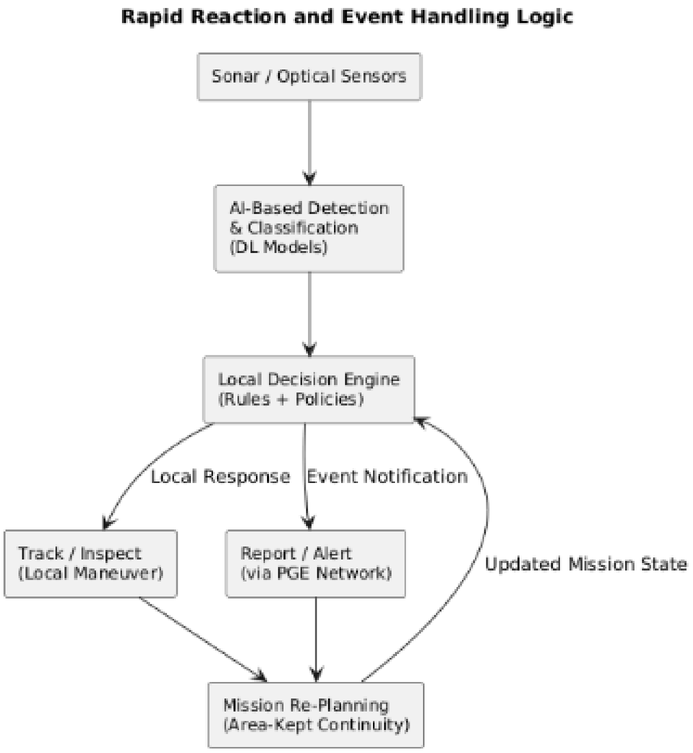

Figure 3. Rapid Reaction and Event Handling Logic Block Diagram

4. Conclusions

This paper presented a unified AI-based autonomous area-maintenance architecture for underwater vehicles operating in GNSS-denied and contested environments. By combining infrastructure-assisted USBL positioning, AI-enhanced sensor fusion, adaptive control, and autonomous power management, the proposed system addresses key limitations of existing AUV solutions, including navigation drift, lack of strict boundary enforcement, and limited mission endurance.

Compared to classical and state-of-the-art AI-based AUV systems, the proposed approach uniquely enables continuous absolute localization, predictive underwater geofencing, rapid autonomous response, and persistent operation in a single coherent architecture. These capabilities make the system particularly well-suited for underwater surveillance, maritime security, and critical infrastructure protection.

Table 1. Comparison of Proposed System with Representative State-of-the-Art AUV Systems.

Feature / Capability	Classical AUV (INS+DVL)	Acoustic-Aided AUV (LBL/USBL)	AI-Based Control AUV	Proposed System (This Work)
GNSS-Denied Operation	✓	✓	✓	✓
Absolute Position Fix	✕ (Drift only)	✓ (Intermittent)	✓ (Intermittent)	**✓ (Continuous via Grid)**
Infrastructure-Assisted Positioning	✕	Partial	✕	**✓ PGE Grid**
AI-Enhanced Sensor Fusion	✕	✕	Partial	✓
Predictive Drift Compensation	✕	✕	✓	**✓ (Navigation + Control)**
Autonomous Area Keeping (Geofenced)	✕	Limited	Partial	**✓ Enforced & Predictive**
Boundary Violation Recovery	✕	✕	Partial	**✓ Automatic Retraction**
Rapid Reaction to Underwater Events	✕	Partial	✓	**✓ Real-Time & Local**
Energy Docking & Persistent Operation	✕	✕	Partial	**✓ Integrated**
Defense-Oriented Design	✕	✓	✓	**✓✓ Explicitly Designed**
Long-Term Autonomous Surveillance	✕	Partial	Partial	**✓ Full Capability**

Future work will focus on experimental validation, cooperative area maintenance with multiple AUVs, and integration of advanced countermeasures and manipulation capabilities to further enhance operational effectiveness.

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